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CESIUM FOUNTAIN DEVELOPMENT AT USNO

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ABSTRACT

In this paper we discuss progress made at the U.S. Naval Observatory (USNO) towards building a cesium fountain atomic clock. In particular we will address the efficacy of a 4-beam optical lattice as an atom collection and launch mechanism. To date we have measured temperatures in a 4-beam lattice of 1.4(0.3) μK and have launched atoms from this lattice to a height of just under a meter with a temperature of 1.7(0.1) μK. We are able to collect 2.4×10^6 atoms using only the lattice beams and no magnetic fields. We have completed the design for and are in the process of fabricating all aspects of the fountain device including the collection region, the drift region, the microwave cavity and the magnetic shields. We will present our progress to date including a discussion of our launch results and the design and testing of our magnetic shields.

1. INTRODUCTION

We have undertaken a research program to produce atomic fountain clocks to support the timekeeping mission of the USNO. The observatory maintains an ensemble of atomic clocks that consists of approximately 50 commercial cesium beam standards and 12 hydrogen masers. These standards are used to compute and produce several time scales, most importantly UTC(USNO).

The most important feature of a fountain clock for the observatory is that it have excellent long term frequency stability. Also important is a short term frequency stability that will allow realization of the long term stability floor in a short (approximately one week) time scale.

Of only minor importance is the frequency accuracy of the standard. The output timescale UTC(USNO) is steered to UTC, which will define the long term frequency. The fact that we do not require frequency accuracy makes it possible to consider atoms other than cesium for our fountain. In addition to the work described here, we have also begun work on a rubidium fountain.

It is our hope to realize a fountain with a short term stability of 1×10^{-13} at one second and a systematic reproducibility of 2×10^{-16} or less. Initially, we will operate by reporting frequency offsets relative to a hydrogen maser that is part of our local clock ensemble. In the long term we hope to use an even more stable local oscillator to take full advantage of the stability that a fountain is capable of reaching [1].

2. LAUNCHING FROM A 4-BEAM OPTICAL LATTICE

2.1 Why are We Interested in a 4-Beam Optical Lattice?

An optical lattice refers to the periodic optical potentials that can exist in the standing wave pattern of multiple overlapped laser beams [2]. With the correct configuration of optical beams (location and polarization), the spatially inhomogeneous adiabatic light shift experienced by the atoms can give rise to a periodic array of potential wells that can trap the atoms. Several possible beam geometries can give this type of optical lattice. In particular, the conventional 6-beam setup used in most fountain designs. However, a 6-beam geometry over-constrains the lattice. That is, small shifts in relative phase between beams will lead to a change in the shape of the potential wells. A 4-beam geometry (Figure 1) is not over-constrained and may allow lower temperatures to be achieved. Indeed, the record low 3-dimensional temperature achieved using only laser cooling techniques was accomplished using a 4-beam geometry [3]. Low temperatures in a fountain are directly related to the amount of signal detected and therefore short term frequency stability.

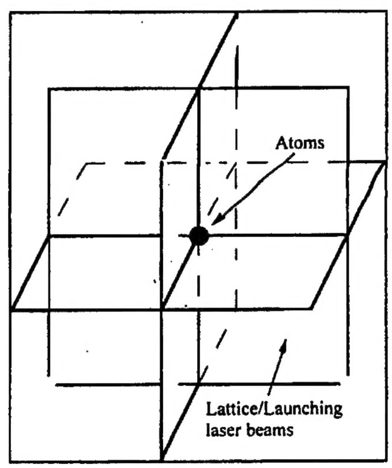

Figure 1: 4-beam optical lattice diagram. In addition to being cooled, the atoms in the lattice can be launched by tuning the two upward going laser beams to a higher frequency than the downward going laser beams.

Another potential advantage to a 4-beam geometry is that with fewer beams, the engineering of the device becomes simpler. For these reasons we decided to investigate the feasibility of a fountain based on collection of atoms into, and launch from a 4-beam optical lattice. In this section, we will discuss the temperatures we have achieved in a 4-beam lattice and the number of atoms we were able to load into this configuration.

2.2 Temperatures in a 4-Beam Lattice

Our initial experiments focused on determining the temperature that we could reach in a 4-beam lattice. To maximize our signal we loaded the lattice from a conventional Magneto-Optical Trap (MOT). This results in more atoms in the lattice, but does not significantly affect the final temperature. Ultimately we would need to load atoms directly into the lattice without the MOT. We consider the number of atoms that can be collected in this way later in this paper.

Our 4-beam lattice uses the geometry shown in Figure 1. Each beam has a linear polarization in the horizontal plane giving a lin $\perp$ lin configuration in the overlap region. The beams have a full width at half maximum (FWHM) of approximately 1 cm and are spatially filtered by single mode polarizing optical fibers resulting in Gaussian profiles. The stabilized intensity used in the initial tests was approximately 2 mW/cm^2/beam. Fine tuning of the power balance between beams is obtained by maximizing the number of atoms transferred from a MOT. The lattice detuning is split into two phases. The first phase for initial capture from the MOT is about 10 MHz red of resonance. The second phase uses a detuning of 78 MHz to the red for lowest temperature. After an initial MOT loading time of about 1 second, both lattice phases had a duration of 2 ms each.

The temperature of the cloud was measured by releasing it into a probe sheet below the collection region and measuring the transit time of the cloud across the probe. The width of this signal is a function of the initial spatial width, the added width due to the expansion, and the width of the probe sheet. One of the largest uncertainties in a measurement of this type is the initial width of the cloud. To measure both the initial width and the expansion of the cloud due to its temperature, we probed the atoms with two sheets: one positioned approximately 4 mm below the collection region and the other approximately 7 cm below the collection region. With this setup we measured longitudinal cloud temperatures of 1.4(0.3) μK.

2.3 Launching from an Optical Lattice

The next step was to determine how well we could launch atoms from a 4-beam lattice and whether we could maintain these low temperatures during a launch. We increased the power to 4 mW/cm^2/beam which allowed us to detune further to the red during the second phase of the launch.

Using a relative launch detuning (up-going vs. down-going) of 6.6 MHz, which corresponds to a launch velocity of about 4 m/s and a launch height of 0.82 m, we were able to achieve launch temperatures of 1.7(0.1) μK.

The transverse and longitudinal directions in the cloud should be in thermal equilibrium [3]. The longitudinal temperature is easier to measure, however it is really the transverse temperature that matters to a fountain because this determines how many atoms will return through the microwave cavity. We can estimate the transverse temperature of the cloud by looking at the number of atoms going up and comparing to the number returning (apertured by the probe sheet size). Some atoms will also be lost to collisions with background gas. The number of atoms interacting with the probe on the return is consistent with the longitudinal temperature and the background pressure as measured by absorption.

To check our launch efficiency, we placed a probe directly above the collection region. We then compared the fluorescence there after the atoms are launched to the fluorescence from before the launch and found that virtually all of the atoms are launched (though, by itself, this test does not guarantee that all of the atoms have been launched correctly – simply that they have left the trap headed upwards).

2.4 Loading into an Optical Lattice – Can We Get Enough Atoms?

Finally, to test the feasibility of a 4-beam launch, it is necessary to determine the number of atoms that can be loaded into a 4-beam lattice without a MOT preloading step. Our design goal for the short term stability of this fountain is $1\times10^{-13}/\sqrt{\tau}$. This type of stability requires a shot-noise limited signal from 10^5 atoms. If we assume a temperature of 2 μK, a cavity aperture of 1 cm diameter and a drift time of 1/2 second then we will see about 20% of the launched atoms return. There is a further reduction by a factor of 9 due to the state selection process, which simply throws away the unwanted states. Consequently, to have 10^5 atoms returning, we must load at least 5×10^6. With our current apparatus the largest number of atoms collected in the 4-beam lattice was 2.4×10^6. It is possible that the number of atoms could be improved upon slightly, however one of the requirements for our fountain is that it be operationally robust. To this end we would like to surpass each of our design goals in the worst case. Since the present number of atoms that we are able to load into a 4-beam lattice is a factor of two lower than needed and the temperatures that we achieved in the 4-beam configuration, while quite good, are not significantly different from those achieved by others in a 6-beam configuration [4] (where larger loads are

easier), we will use a 6-beam configuration for our first design.

3. MAGNETIC SHIELD DESIGN AND INITIAL TESTS

3.1 Shielding Requirements

As with other aspects of our fountain clock, operational robustness is a guiding principle in determining our shielding requirements. While it is possible to get extreme reduction in magnetic field values by using a combination of shields and shim coils, the better we can do with shields alone, the simpler and more reliable our system will be. The sensitivity of the $|3,0\rangle \rightarrow |4,0\rangle$ clock transition to magnetic fields is through the quadratic Zeeman shift. The value of the shift is $f_Z = 427\ B^2\ \text{Hz/G}^2$ where B is the field in Gauss. Since the USNO fountain will be optimized for precision as opposed to absolute accuracy, we are primarily concerned with the fluctuations in f_Z rather than the absolute value of the shift. By taking the derivative we have $\Delta f_Z = 854\ B\ \partial B$ where δB are the fluctuations in the field. Our design goal calls for the fractional frequency fluctuations caused by any systematic effect to be below the 10^{-16} level. Thus in this case we require $\Delta f_Z/f \leq 10^{-16}$ where $f \approx 9.2$ GHz. Since we intend to use a bias field of 1 mG, this means that we need $\delta B \leq 1 \mu G$.

If we assume ambient fluctuations in the field of about 5 mG then to reach our design goal for field stability inside the fountain, we will need shields with a shielding effectiveness of 5,000. Fountain designs usually call for a cylindrical shield geometry. Since longitudinal shielding effectiveness is usually smaller than radial shielding effectiveness in cylindrical shields, we set our goal of 5,000 for the longitudinal shielding.

3.2 Modeling Shielding Effectiveness

Because only approximate closed form solutions of limited validity exists for the fields inside a highly permeable cylinder [5] we decided to model candidate shield designs using a software package designed for this purpose.

Specifically, among the issues we wanted to obtain quantitative information on were: the optimal shield spacing in a multi-shield set, the effect of holes in the endcaps, the effect of placing sleeves on holes in the endcaps, the effect of rounding corners, endcap shape and material thickness.

For the model we consider a set of three concentric cylindrical shields, each closed at both ends with an endcap. Each endcap has a 5 cm diameter hole in the center to accommodate vacuum apparatus. We chose a shield material with a permeability of 10^5 (similar to Carpenter's HYMU80 – see below) and a thickness of 2 mm. The inner shield diameter and length were constrained to 21 cm and 71 cm by the size of the vacuum chamber and cavity.

To address the question of optimal shield spacing, we held the ratio, R, of adjacent shield diameters constant for a given shield set and then calculated the shielding effectiveness for several values of R. We held the axial spacing to 5 cm between all endcaps in all cases.

The model suggests that the longitudinal shielding effectiveness for R = 2.0 is 30 times better than for R = 1.1. See Figure 2. In fact, the model predicts that the shielding effectiveness is still increasing as R is varied past 3. Since the amount of material needed quickly becomes prohibitive as R is increased, it is useful to note that according to the model, a shield set with R = 2 already has a shielding effectiveness at the center within 15% of that corresponding to R = 3. Therefore we have chosen a ratio of 2 for our shield set.

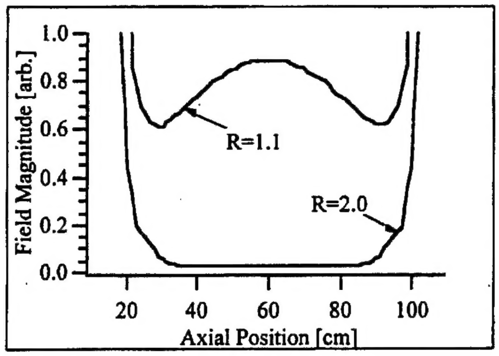

Figure 2. Numerical modeling of shield spacing suggests that a shield spacing ratio of 2.0 has an overall factor of 30 times better shielding effectiveness than for a ratio of 1.1 and significantly better uniformity.

When comparing closed endcaps to endcaps with an axial hole (to allow for vacuum apparatus), we found that the closed endcaps didn't improve the shielding effectiveness at the center, but when compared to endcaps with 5 cm diameter holes, did extend the homogeneity from 80% of the shield length to about 95%. This makes the usable region of the shields larger, but can be easily compensated for by making the shields slightly longer.

By placing a 5 cm long cylindrical sleeve on the two holes (one on each end) in the outer shield, and 2.5 cm sleeves on the other endcap holes, the model suggests a factor of 27 times improvement in uniformity over 80% of the length of the inner shielded region.

The model showed only modest improvements (roughly 10%) for rounding edges or making the corners greater than 90° (conical endcaps). However

these results are highly dependent on the thickness of the material chosen.

Our model predicted a factor of 2-3 times improvement in shielding effectiveness for an increase in thickness from 1.5 mm to 2 mm. Obviously things will continue to improve with thickness, but will also become prohibitively expensive and heavy. Beyond 2 mm, it is probably better to simply add additional cylinders.

3.3 Shield Design

Based on the modeling information just described we have designed our shield set and had it fabricated. It has several unconventional features. First, we use 0.062" (1.5 mm) material. The material is Carpenter HYMU80, which is MIL SPEC N-14411 "comp-1". This has a permeability approximately 2 times higher than conventional "mu metal", which is referred to as "comp-2". Our first choice for thickness was 2 mm, but this was not available in comp-1 material. Our shield set consists of 3 shields with a radial spacing ratio of about 2. The inner shield has a diameter of 21 cm and a length 71 cm. The outer shield has a diameter of 80 cm and a length of 91 cm. Each endcap has a 5 cm hole in it with a 2.5 cm sleeve attached to the inner holes and a 5 cm sleeve attached to the outer most holes. The corners between the shield walls and the endcaps are all 90°.

The conventional technique for mating endcaps to walls is to add a sleeve to the outer edge of the endcap that fits around the shield wall. In principle this can be quite effective, but it is very sensitive to the machining tolerances of the two pieces. To reduce this sensitivity we place a flange on each end of the shield wall. Rather than fitting around the wall, the endcap simply sits flush on top of the flange. We then add bolted aluminum rings on each side to press the two pieces together obtaining a minimal gap. This approach is insensitive to the relative diameters of the two pieces being mated and only requires a modest flatness be maintained across their surfaces.

Finally, we have built a low-noise, precision current source to drive the solenoid that will create the 1 mG bias field. This current source supplies 100 μA with short term noise of 1 $nA/\sqrt{Hz}$ from 0.1 to 10 Hz and long term instability below 1 nA. Thus, the bias field should be stable to better than a part in 10^5.

3.4 Initial Tests

We have taken initial measurements on our new shield set and find its longitudinal shielding to be better than 9,000, exceeding our goal by a factor of 2 or more. This value is a lower bound established by the resolution of our measurement system. The actual value may be higher, but must await an atomic signal for more precise measurement.

4. FUTURE PLANS

As of this writing, the design of our cesium fountain is complete. Many subsystems, such as the laser system, optics, atom collection, electronics, computer control, vacuum systems, support superstructure, frequency chain and shields have been built or ordered. Others, such as the microwave cavity, drift region and solenoid are being fabricated and nearing completion. We hope to be finished with construction soon and beginning the device characterization. Concurrent with this work we will be building a rubidium fountain, that may have even better systematics than the cesium fountain [6].

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